INTERNATIONAL JOURNAL OF RESEARCHES IN BIOSCIENCES, AGRICULTURE AND TECHNOLOGY
© VISHWASHANTI MULTIPURPOSE SOCIETY (Global Peace Multipurpose Society) R. No. MH-659/13(N)
www.vmsindia.org

EFFECT OF PROCESS PARAMETERS ON TENSILE STRENGTH OF FRICTION STIR WELDED Al-Cu-Mg-Si-SiC$_p$ COMPOSITE

Subramanya R Prabhu B[1], Arun Kumar Shettigar[1], Karthik Rao M C[2], Akshay Nigalye[3], Mervin A Herbert[2] and Shrikantha S Rao[2]

[1]Mechatronics Engineering Department, Manipal Institute of Technology, Manipal
[2] Mechanical Engineering Department, National Institute of Technology, Surathakal
[3]Department of Mechanical Engineering, Goa College of Engineering, Goa, India
subramanya.prabhu@manipal.edu

Abstract—In this study, application of friction stir welding (FSW) process to join stir casted aluminium–copper matrix-based composites reinforced with SiCp is investigated. FSW is a novel solid state joining technology in which a non-consumable rotating tool is used to produce frictional heat between the rotating tool and fixed work piece in order to make weld joint. The welding parameters such as welding speed, tool rotational speed, and profile of the tool were considered for analysis. An attempt is made to investigate the effect of process parameters of FSW on the ultimate tensile strength (UTS) of the welded joints. Rotational speed, welding speed and tool pin profile in the order considered are found to be the major influencing parameters on the joint strength. Optimization of process parameters is carried out using Taguchi L18 orthogonal array design. Based on the analysis of variance, optimum process parameters are identified and validated by confirmation tests.

Keywords—Friction stir welding, Metal matrix Composite, Taguchi, Ultimate Tensile strength.

Introduction

Friction stir welding process has made tremendous contribution towards the joining of aluminium, aluminium alloys, copper, steel, magnesium, composites and even dissimilar metals. FSW is solid state welding process, capable of joining materials which can be hardly joined with common fusion welding techniques. Since FSW does not involvemelting of material, the common problems of fusion welding process suchas solidification and liquation cracking, loss of volatile alloying elements and porosity at weld region can be prevented.[1]. Even though it has lot of advantages, there are chances of abnormality of weld due to inadequate selection of process parameters. Hence, selection of process parameters and analysis of these process parameters play a key role in obtaining higher joint strength. Several researchers have put a lot of effort in understanding the influence of process parameters on the material flow, microstructureand mechanical properties [2]-[3]. Most of them have used classical experimental techniques to explore the influence of the process parameters by varying one parameter at a time while keeping others constant. Such kind of approach leads to increase in the cost and time of experiments.

Taguchi and Konishihave developed statistical technique to analyse and optimize the engineering problems in order to study the performance characteristics of selected design parameters. It is a powerful technique with simple approach and is proficient in identifying the best range of values for design parameters. More or less, few researchers used orthogonal array technique to enhance the optimum levels of process parameters [1]-[5].Reference [1] successfully adopted Taguchi design of experiment for friction stir welding of aluminium alloy by considering rotational speed, welding speed and axial force as process parameters to evaluate the contribution of each process parameter on tensile strength of the alloy joints. Multi-objective optimization of friction stir welding process parameters for AA5083 was carried out by [4] using Taguchi based Grey relation analysis. The process parameters are rotational speed, welding speed and axial force, correlating the ultimate strength of the joint. The effect of tool pin profile on tensile strength of the aluminium alloys are analysed by considering the rotational speed, welding speed and tool plunge depth as a process parameters was studied by [5].

The static to dynamic ratio of the FSW tool is influencing factor on improving the quality of the joint. There is more information available on performance of different tool geometries. However, till date only a few studies have been carried out regarding the combination of the two different geometries of the single tool.This combination geometry helps in obtaining the different static to dynamic ratio of tool and also in obtaining individual benefits.

Methodology

Standard Orthogonal array designs are selected based on process parameters, their levels and interaction effects. The welding process consists of three control factors, namely, rotational speed, welding speed and tool profile. Three levels per factors were selected based on the initial stage of experiment. The selected level is in such a way that it must be free form defects such as pin hole, worm hole and tunnel defect. The experiments were conducted for AA6061-4.5%Cu-5%SiC and AA6061-4.5%Cu-5%SiC. Therefore, composition level is also selected as one of the input parameters. Since it has 2 levels, mixed level OA is selected for the analysis. According to Taguchi design of experiments method, the available designs for analysis are L18, L36 and L54. The number of degrees of freedom is less than the 18. Therefore L18 is used for the analysis. The implication of OA design will reduce the experiments from 54 to 18 experiments. The factors and their levels are tabulated in Table 1.Ultimate tensile strength of the composite joint is considered as response of the system. The influence of the process parameters on the response are assessed through their means and signal to noise (S/N) ratios. The effect on average outcome is indicators of signals. The noise is a measure of deviations from the sensitivity of the experiments' response to the noise factors. Since higher ultimate tensile strength is required, a 'Higher is better' criterion is selected for the analysis. The deviation of the quality characteristic from the experimental values is determined using S/N ratio and is represented by following equation:

$$\eta_M = -10\log\left[\frac{1}{n}\sum Y_{lmn}^2\right] \qquad (1)$$

Where n is number of tests, and Y_{lmn} is the experimental conditions of the lth quality characteristics in the m^{th}experiment at the nth test.

After performing the analysis, the experimental response results are represented in terms of means of ultimate tensile strength and equivalent S/N ratio.

The experiments were performed on 6 mm thickness aluminium metal matrix composites. The composition of the matrix is shown in Table 2. This matrix is reinforced with 5% SiC particles using stir casting process. The joining of these plates was carried out on vertical milling machine (make BFW) of 5.5kW power. The FSW setup has been shown in Figure 1. The vertical head of milling machine was tilted to an angle of 2° away from the tool travel path.The base material proceeds in the direction of tool motion due to increase of contact pressure caused by the backward tilt of the tool.Threaded pin profile (TPP), combination of Threaded and Square pin profile (CSTPP) and Square Pin profile (SPP)tool are used in the present study. The static to dynamic ratio of TPP, CSTPP and SPP tools are 1.01, 1.17 and 1.26 respectively. Reference [6] have promulgate that, the enhancement in mixing capacity of a given geometry is achieved due to the changes in the ratio of dynamic volume to static volume. While the Dynamic volume refers to the volume being swept by the pin during rotation and static volume refers to the volume of the pin.The tools are hardened to a hardness of 53HRC. The welded specimens are sliced to perform the tensile test using wire electro discharge machining (2014). The tensile test specimens were prepared by following the ASTM E8-04 standards. From each of the welded specimens, three tensile test samples are prepared and average values are considered for the analysis. Computerized tensometer is used to conduct the tensile test (make: Kudale P2000).

Results and Discussion

In order to analyse the effect of design factors namely, rotational speed, welding speed, tool pin profile and weight percentage of SiC particles, and the interactions on the experimental data, analysis of variance is performed at 95% level of confidence. Table 3 and 4represent the ranking of each welding process parameters using Taguchi design of experiment and Analysis for S/N ratio and means (larger is better) obtained at different process parameter levels. The term 'delta' in Table 3 and 4 present extreme alter of UTS due to factorial variation. Larger variation in the delta value indicates that the response is highly significant with respect to the factors under consideration. From the Table 3 and 4, it can be inferred that composition of the hard particles is the most significant factor influencing UTS. The next significant factor is rotational speed. Tool pin profile and welding speed have shown minimal effect on UTS factor in FSW of composites

The relative emphasis of the factor effects are further analysed using analysis of variance (ANOVA). The ANOVA is carried out for means. Table 5 and Table 6 present the results of ANOVA for S/N ratio and Means of the UTS factors, respectively. The most influencing factors on the mean and variations can be identified from Table 5 and Table 6. The results stipulate that composition, rotational speed, welding speed, and tool profile are the consequential parameters, which affect the UTS factor. The interaction between the composition and rotational speed does not have significant effect on the UTS of composite joined using friction stir welding. Percentage contribution (P%) is the ratio of sum of square to total sum of square, which is relatively used to measure the prominence of each term present in the model.From the appraisal of the P% of the different factors for UTS, it can be seen that composition factor has the highest contribution of 72.43%. Rotational speed has the second highest contribution of 14.70%. The third factor tool pin profile has a contribution of 4.90%. Finally, the contribution of welding speed is 8.63 %. The error is 0.91%. Thus composition is the most vital factor to be taken into consideration while friction stir welding of composite, followed by rotational speed, welding speedand tool profile.

Based on the above analysis, the optimum welding parameters for maximization of UTS can be calculated by considering the significant factors having highest values of S/N ratio and mean levels. The optimized condition obtained for the process is [7],

Predicted S/N (maximization UTS)=Composition 2 + rotational speed 2 + welding speed 3 + tool pin profile 3 – 3(n) (2)

= 45.99+ 45.43+ 45.07+44.86-3(44.45) = 47.97

Predicted mean (maximization UTS)=202.2 +189.9+182.1+174.4- 3(170.61)

=237.74 N/mm^2, where n represents the average value of S/N ratio in equation 2.

Confirmation test

The above combination of experimental conditions is not available on the L18 experiment. Hence, predicted optimum value of UTS is verified by conducting experiment on the combination obtained from equation 1. The average of UTS obtained from the experiment is 243.3 N/mm^2. The confidence interval for S/N ratio is within the range.The optimal joint strength fall within the selected range of process parameters, as the selected process parameters results in defect free weld and joint strength.

Figure 2 depicts the mean effect plot of factors effect on UTS of the composites joined through friction stir welding. The data mean value is used to analyse the effect of each factor. Figure 2 shows that composition, rotational speed, welding speed and tool pin profile have significant effect on UTS of the friction stir welded composite. In addition, from Figure 2, it can be seen that an increase in composition from 5% SiC to 10% SiC exhibited increase in the UTS. The increase in UTS may probably be due to the SiC particles preventing the movement of dislocations in the microstructure. This dislocation increases the dislocation density, which provides benefit to increase the strength of the composite. There is decrease in the inter-particle distance between the reinforcement particles, which results in increased resistance to dislocation motion as the particulate content is increased. During deformation, either the matrix material has to push the hard particulate further or it has to bypass the particles for deformation. During the process, the dislocations pile up. This restriction in the plastic flow in the matrix provides enhanced strength to the composite.The increase in the hard particles probably results in increase of dislocation density, because of which the UTS increases.

The increase in rotational speed from 710 rpm to 1000 rpm results in expansion of the ultimate tensile stress region. With further increase in the rotational speed, the ultimate tensile strength decreases. Heat generation due to friction is principally dependent on the rotational speed [3]. Lower rotational speed yields lesser, heat generation, irrespective of the welding speed. Subsequently, heat supplied to the base material is reduced. This effect causes insufficient material flow and less plasticization in the stir zone. Hence, ultimate tensile stress is lowered. The higher rotational speed yields higher heat generation, irrespective of the welding speed. Subsequently, the heat supplied to the base material is higher. This effect causes turbulence in material flow and grain coarsening in the stir zone. This causes reduction in the ultimate tensile stress. Neither low heat input nor high heat input is preferred in the FSW.

The significant increase in the welding speed exhibited increase in ultimate tensile strength. The softened area is diminished as the welding speed increases [3]. Thus ultimate tensile stress has proportional relationship with welding speed. Lower welding speed is associated with higher heat input, which results in lower cooling rate of welding joint. This can significantly increase the size of the grain; hence ultimate tensile stress is reduced. When welding speed is less than the critical value, the FSW can produce defect-free joints when welding speed is higher than the critical value, weld defects may be produced in the joint. These defects act as crack initiation sites during tensile test.

The tool profile analysis showed that, the SPP profiled pin is better than CSTPP and TPP. This is attributed to static volume to dynamic volume ratio which results in grain refinement and annealing during the welding process, and more number of pulsating actions (60 pulses/sec) of the tool. Square profile tool sweeps larger amount of material as compared to other types of tool. The joint fabricated by CSTPP tool showed close values of ultimate tensile stress as that exhibited by SPP tool. This is due to less DV/SV ratio. The ultimate tensile stress produced by the TPP tool is lower than that by other tools. The frictional heat produced by the TPP tool is less than the other tools because of lesser contact area and also due to the absence of pulsating effect.

Microstructure analysis of FS welded composite

Figure 3 shows the nugget zone microstructure of the Al-Cu-Mg-Si-10%SiC composite friction stir welded at rotational speed of 1000 rpm and welding speed of 80 mm/min fabricated using SPP tool.The average grain size obtained at NZ is 2.13±0.14 microns. This is due to the fact that stirring action of the tool at the weld center produces plastic deformation resulting in fine grains. This region undergoes high plastic deformation. Frictional heat induced by stirring action of the tool, in turn results in the rearrangement of particles from agglomerated and heterogeneous distribution in the base metal to homogeneous distribution in weld NZ. Usually, the dislocation density at NZ is low [8]. The NZ comprised of numerous small particles as compared to the base material [9]-[10]. This is due to the striking of hard particles amongst each other and also abrasive action of the rotating tool, resulting in numerous small particles. Stirring action of the tool distributes small particles uniformly in the NZ. The uniformly distributed small particles leads to increase in the load bearing capacity of the composite [11]. Therefore, increase in the weight percentage of SiC particles led to increase in the hardness and strength. The NZ exhibited an increase in the hardness by 27% (134 HV) as compared to the hardness of 105±3HV base material.

Figure 4 present the fracture surface of AA6061-4.5(wt%)Cu-10 (wt%) SiC composite joint friction stir welded using SPP tool. The macroscopic and microscopic examination of the fracture surface reveals ductile failure. It is characterized by dimples with tearing edges. All the samples, irrespective of process parameters and tool profile, are seen to be broken at HAZ where minimum hardness was found during hardness measurement, in a direction normal to the tensile stress axis.

Table 1. Control factors at different levels of the experiment

CONTROL FACTOR	LEVEL-1	LEVEL-2	LEVEL-3
Composition	5	10	----
Rotational Speed (rpm)	710	1000	1400
Welding Speed (mm/min)	50	63	80
Tool Pin Profile	1 (TPP)	2 (CSTPP)	3 (SPP)

Table 2. Chemical composition of composite.

Aluminium	Copper	Magnesium	Silicon	Manganese	Iron
Remaining	4.5	1	0.6	0.15	0.7

Table 3. S/N ratio value table of UTS

Level	Composition (%)	Rotational Speed (rpm)	Welding Speed (mm/min)	Tool Profile
1	42.92	44.06	43.78	44.06
2	45.99	45.43	44.52	44.45
3	----	43.89	45.07	44.86
Delta	3.06	1.54	1.29	0.80
Rank	1	2	3	4

Table 4. Means value table of UTS

Level	Composition (%)	Rotational Speed (rpm)	Welding Speed (mm/min)	Tool Profile
1	141.1	162.4	158.3	163.5
2	200.2	189.9	171.1	171.0
3	----	159.2	182.1	177.4
Delta	59.1	30.7	23.5	14.0
Rank	1	2	3	4

Table 5. ANOVA for S/N of UTS of composite joined through Friction Stir welded

Source	DF	Seq SS	F-Ratio	P-Value	P%
Composition (%)	1	42.2414	639.55	0	72.43
Rotational speed (rpm)	2	8.5738	64.91	0	14.70
Welding speed (mm/min)	2	5.0333	38.1	0	8.63
Tool profile (T1 CST2 S3)	2	1.9095	14.46	0.002	3.27
Composition (%)* Rotational speed (rpm)	2	0.0378	0.29	0.758	0.06
Residual Error	8	0.5284	---	---	0.91
Total	17	58.3242	757.31		100

DF= Degree of Freedom, Seq SS = Sequential Sum of Square, F= Fisher's ratio, P= Probability.

Table 6. ANOVA for Means of UTS of composite joined through Friction Stir welded

Source	DF	Seq SS	F-Ratio	P-Value	P%
Composition (%)	1	15727.5	658.38	0	72.69
Rotational speed (rpm)	2	3395.9	71.08	0	15.70
Welding speed (mm/min)	2	1658.5	34.71	0	7.67
Tool profile (T1 CST2 S3)	2	587.2	12.29	0.004	2.71
Composition (%)* Rotational speed (rpm)	2	75.5	1.58	0.264	0.35
Residual Error	8	191.1	---	---	0.88
Total	17	21635.7	778.04		100

DF= Degree of Freedom, Seq SS = Sequential Sum of Square, F= Fisher's ratio, P= Probability.

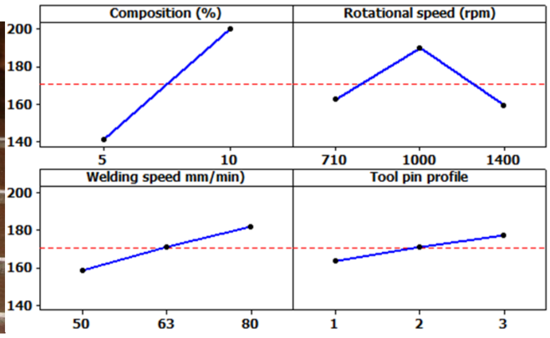

Figure 1. FSW setup **Figure 2** Main effects plot for means of Friction Stir Welded composites

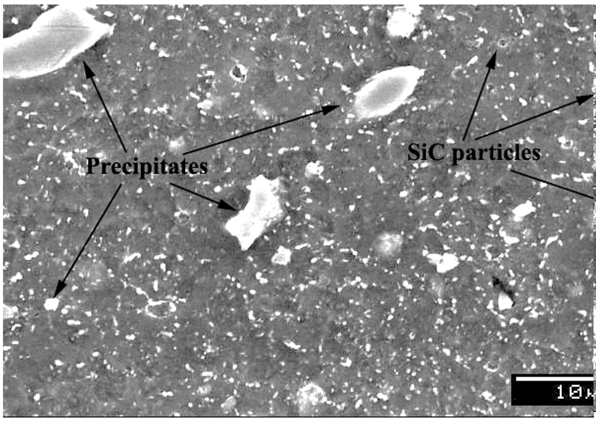

Figure 3. Nugget zone SEM image of Al-Cu-Mg-Si-10% SiC

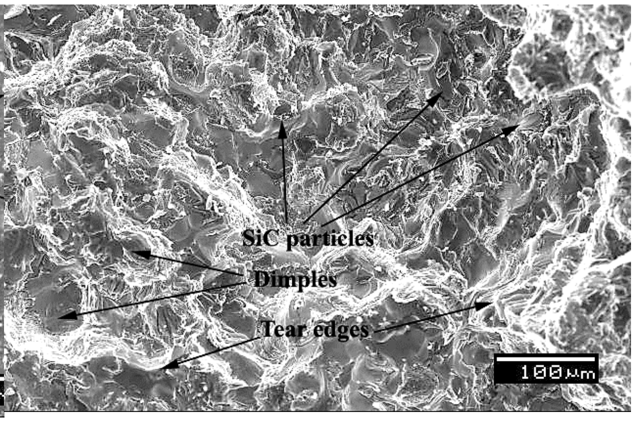

Figure 4. Facture surface of friction stir welded composite

Conclusions

1. Optimal values of rotational speed, welding speed, type of pin profile and weight percentage of SiC particles for achieving maximum UTS have been identified. It is found that weight percentage has 72.43% contribution, rotational speed has 14.70% contribution, welding speed has 8.63% contribution and tool pin profile has 3.27% contribution to ultimate tensile strength of the joint.
2. Weight composition of SiC particle and rotational speed of the tool showed highest contribution towards maximizing the ultimate tensile strength.
3. A good agreement has been arrived at between the optimized values of process parameters obtained from analysis of variance (ANNOVA) and those by the validation experiments.
4. The grains and SiC particles are found to be decreased due to stirring action of the tool resulting in dynamic recrystallization at nugget zone. Hence, hardness of the composite found to be more at nugget region than the base material.

References

[1] A. K. Lakshminarayanan, V. Balasubramanian, "Process parameters optimization for friction stir welding of RDE-40 aluminium alloy using Taguchi technique." *Trans,. Nonferrous Met. Soc. China, (*2008), pp. 547-554.

[2] Nami, H., Adgi, Sharifitabar and Shamabadi, "Microstructure and mechanical properties of friction stir welded Al/Mg2Si metal matrix cast composite." *Mater Des, 32* (2011), 976-983.

[3] Periyasamy, P, Mohan, B., Balasubramanian, V., Rajakumar, S. and Venugopal, S. "Multi-objective optimization of friction stir welding parameters using desirability approach to join Al / SiC p metal matrix composites." *Tran Nonfer Met Soci China., 23(4)* (2013), 942-955.

[4] SundaravelVijayan , R. Raju and S. R. K Rao, "Multiobjective Optimization of Friction Stir Welding Process Parameters on Aluminum Alloy AA 5083 Using Taguchi-Based Grey Relation Analysis." *Materials and Manufacturing Processes*. (2010), 25, pp. 1206-1212.

[5] S. Suresh N. ShenbagaVinayagaMoorthi, "Process development in stir casting and investigation on microstructures and wear behavior of TiB2 on Al6061 MMC." *Procedia Engineering*, (2013), 64, pp. 1183 – 1190.

[6] Elangovan, K., &Balasubramanian, V. "Influences of tool pin profile and welding speed on the formation of friction stir processing zone in AA2219 aluminium alloy". *J Mater Process Techno,*(2008), 200, 163–175.

[7] Tansel I N,Gulmez, Demetgul, "Taguchi Method-GONNS integration: Complete procedure covering from experimental design to complex optimization", *Expert Systems with Applications38* (2011) 4780 - 4789

[8] Mishra, R.S. and Ma, Z.Y. "Friction stir welding and processing" *Mater SciEng R*, (2005), 50, pp. 1–78.

[9] Arunkumar, Giridhar, Mervin Herbert and Shrikantha Rao. "Microstructural Characterization and hardness evaluation of friction stir welded composite AA6061-4.5Cu-5SiC (wt.%)", *Defence Science Journal* 63(4), (2013), 1-6.

[10] Arun Kumar, VeereshNayak, Mervin A. Herbert and Shrikantha S. Rao (2014). "Microstructure and hardness of friction stir welded aluminum-copper matrix based composite reinforced with 10wt.% SiCp". *Matrial Research Innovation, 18*, (2014), 84-89.

[11] Ashok Kumar and Murugan "Optimization of friction stir welding process parameters to maximize tensile strength of stir cast AA6061-T6 / AlN p composite." *Mater Des*, (2014). 57, 383-393.